Design of Triple-Frequency Microstrip-Fed Monopole Antenna Using Defected Ground Structure

Wen-Chung Liu, *Senior Member, IEEE*, Chao-Ming Wu, and Yang Dai

***Abstract*—A novel triple-frequency microstrip-fed planar monopole antenna for multiband operation is proposed and investigated. Defected ground structure (DGS) is used in this antenna, which has a rectangular patch with dual inverted L-shaped strips and is fed by a cross-shaped stripline, for achieving additional resonances and bandwidth enhancements. The designed antenna has a small overall size of $20 \times 30\ \mathrm{mm}^2$, and operates over the frequency ranges, 2.14–2.52 GHz, 2.82–3.74 GHz, and 5.15–6.02 GHz suitable for WLAN 2.4/5.2/5.8 GHz and WiMAX 3.5/5.5 GHz applications. There is good agreement between the measured and simulated results. Experimental results show that the antenna gives monopole-like radiation patterns and good antenna gains over the operating bands. In addition, effects of both the length of the protrudent strips and the dimensions of the DGS for this design on the electromagnetic performance are examined and discussed in detail.**

***Index Terms*—Defected ground structure, monopole antenna, multi-band, triple-frequency, WiMAX, WLAN.**

I. Introduction

RECENTLY, the demand for the design of an antenna with triple- or multiband operation has increased since such an antenna is vital for integrating more than one communication standards in a single compact system to effectively promote the portability of a modern personal communication system. For this demand, the developed antenna must not only be with a triple/multiband operation but also have a simple structure, compact size, and easy integration with the circuit. Among the known triple/multiband antenna prototypes, the planar monopole antenna with various structures has become a familiar candidate because of its attractive characteristics including low profile and weight, low cost, and versatile structure for exciting wide impedance bandwidth, dual- or multiresonance mode, and desirable radiation characteristics. However, the difficulty in designing antenna challenges engineers when the size of the antenna reduces and the number of operating frequency bands increases. So far, for size reduction, bandwidth enhancement, and resonance-mode increment, numerous monopole antennas have been proposed by employing various promising feed structures such as the probe [1]–[5], the microstrip [6]–[9], and the coplanar waveguide (CPW) [10]–[14]. In these presented monopole antennas, a large solid ground plane having the shape of a square, rectangle, circle, or ellipse is usually adopted. Different from this, a notable ground structure named defected ground structure (DFG) has recently been investigated and found to be a simple and effective method to reduce the antenna size as well as excite additional resonance modes [15]–[18].

In this paper, a small and low-profile microstrip-fed monopole antenna for triple-frequency operation is proposed. The radiating element was modified by loading it with protrudent strips and feeding it with a cross-shaped stripline. In addition, unlike the conventional microstrip-fed antenna prototype using a solid ground plane, in this design the ground was cut out by shaped slots and thus forms a DGS. The above design skills are introduced to approach excitation of triple resonant modes accompanied with good impedance bandwidths over the operating bands. By properly selecting the dimensions of the proposed antenna, good triple-broad impedance bandwidths and radiation characteristics suitable for two multiband wireless communication systems such as the wireless local-area network (WLAN) 2.4/5.2/5.8 GHz and the worldwide interoperability for microwave access (WiMAX) 3.5/5.5 GHz operations can be achieved. In addition, with the DGS, the proposed antenna can avoid a large surface-wave loss and thus decrease its impact on the coupling effect when it is used as an array element. The antenna configuration and simulated data as well as the constructed prototype and measured data will be carefully examined and discussed in Sections II and III.

II. Antenna Design and Simulation

The schematic configuration of the proposed microstrip-fed planar monopole antenna with defected ground structure (DGS) for triple-frequency operation is shown in Fig. 1. For the design studied here, the radiator and ground plane are etched on the opposite sides of a printed-circuit board (PCB) with a dielectric constant of 4.4 and substrate thickness of 1.6 mm.

A cross-shaped stripline, which comprises both the vertical and horizontal strips with dimensions of $L_1 \times W_1$ and $L_2 \times W_2$, respectively, and a distance of d_1 between the horizontal strip and the feed point, is used for feeding the radiator. The basis of the radiator is a rectangular patch, which has the dimensions of length L_3 and width W_3, and is protruded with two inverted L-shaped strips from the patch's upper two sides. Each of the two strips comprises both the vertical and horizontal strips with dimensions of $L_4 \times W_4$ and $L_5 \times W_5$, respectively. As for the ground plane, unlike the general use of a solid rectangular plane for a microstrip-fed antenna, it is defected by two equal-shaped

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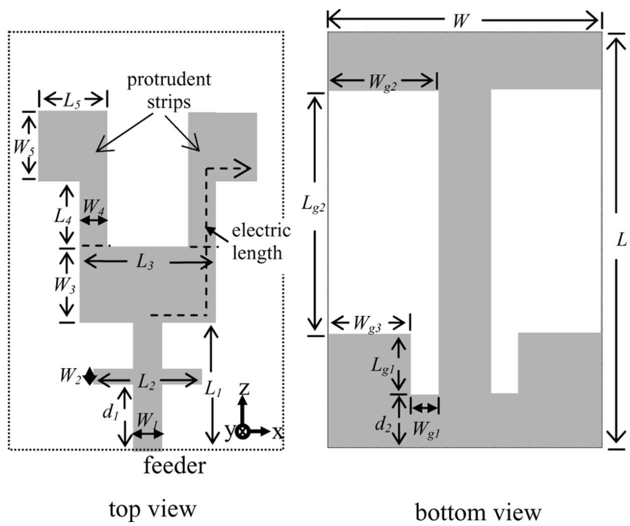

Fig. 1. Schematic configuration of the proposed triple-frequency monopole antenna with defected ground structure.

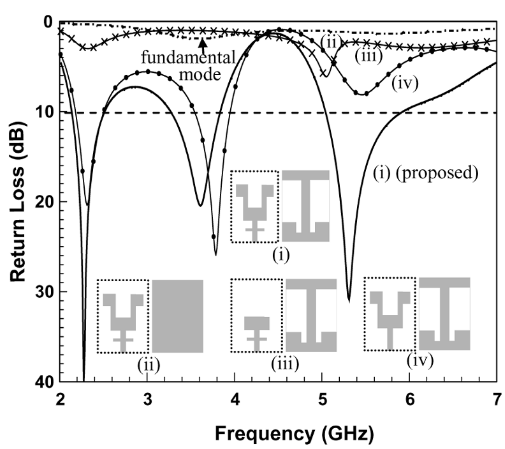

Fig. 2. Simulated return loss against frequency for the proposed antenna with/without DGS, protrudent strips and cross-shaped feedline.

slots, which were appropriately embedded from the ground's left and right sides. These slots were introduced to increase the excitation of resonant modes and improve the impedance matching condition for the proposed antenna. The overall size of the ground is $L \times W$, and each of the embedded slots has a vertical section of $L_{g1} \times W_{g1}$ as well as a horizontal section of $L_{g2} \times W_{g2}$. Meanwhile, the slot is etched with a distance of d_2 from the bottom of the ground and its vertical section has a distance of W_{g3} from the ground side edge.

The electromagnetic solver, Ansoft HFSS, was used to numerically investigate and optimize the proposed antenna configuration. Fig. 2, trace (i), shows the simulated return loss of the proposed antenna with the optimized parameters as listed in Table I. Obviously, the simulation results show three resonant bands at frequencies of 2.26, 3.6, and 5.3 GHz with bandwidths, defined for 10-dB return loss, of about 380 MHz (2.13–2.51 GHz), 570 MHz (3.26–3.83 GHz), and 880 MHz (5.03–5.91 GHz), respectively, corresponding to an impedance bandwidth of 17%, 16% and 17% with respect to the appropriate resonant frequencies over the three operating bands. Apparently, the above obtained bandwidths simultaneously cover the WLAN

TABLE I
OPTIMAL GEOMETRICAL PARAMETERS OF THE PROPOSED TRIPLE-FREQUENCY MONOPOLE ANTENNA

Parameter	L	W	L_1	W_1	L_2	W_2	L_3	W_3	L_4	W_4
Unit(mm)	30	20	9	2	8	1	10	6	5	2
Parameter	L_5	W_5	L_{g1}	W_{g1}	L_{g2}	W_{g2}	W_{g3}	d_1	d_2	
Unit(mm)	5	5	4	2	18	8	6	5	4	

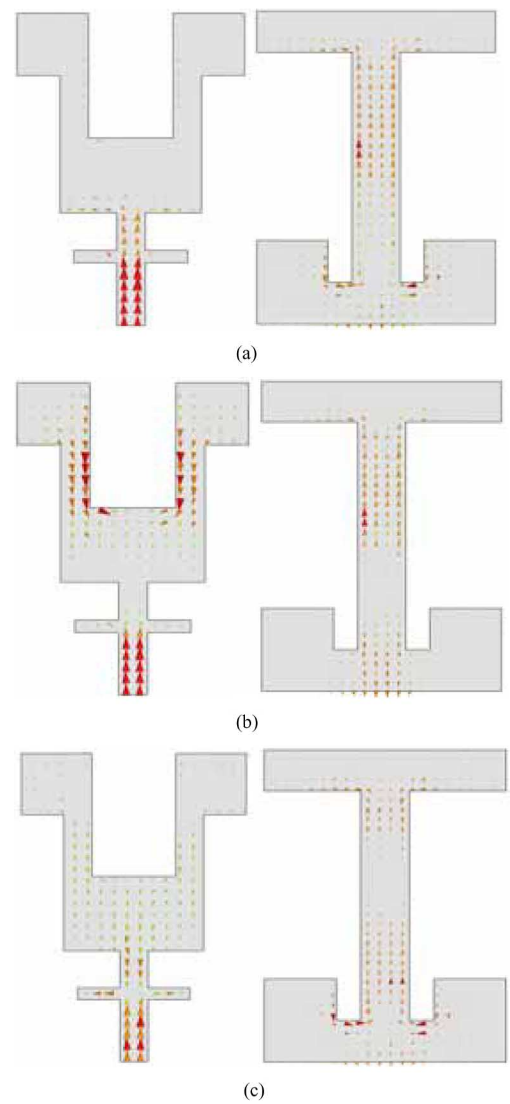

Fig. 3. Simulated results of the surface current distributions for the proposed triple-frequency monopole antenna studied in Fig. 2 at (a) 2.26, (b) 3.6, and (c) 5.3 GHz.

standards in the 2.4/5.2/5.8 GHz bands and the WiMAX standards in the 3.5/5.5 GHz bands. To further examine the appropriate impedance matching condition caused from addition of the DGS, the protrudent strips, or the cross-shaped feedline, the return loss for the proposed optimal design (case (i)) but without using the DGS, without having the protrudent strips, or without the horizontal strip for the feedline, which are denoted as curves (ii), (iii), and (iv), respectively, are also analyzed and presented

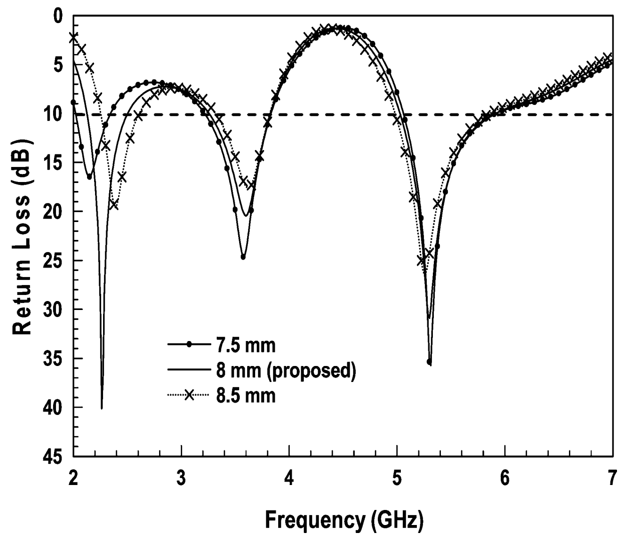

Fig. 4. Simulated return loss against frequency for the proposed triple-frequency monopole antenna with various W_{g2}; other parameters are the same as listed in Table I.

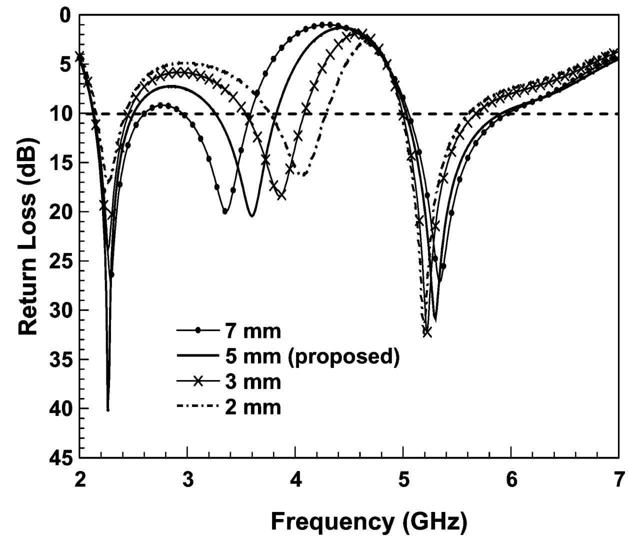

Fig. 5. Simulated return loss against frequency for the proposed triple-frequency monopole antenna with various L_5; other parameters are the same as listed in Table I.

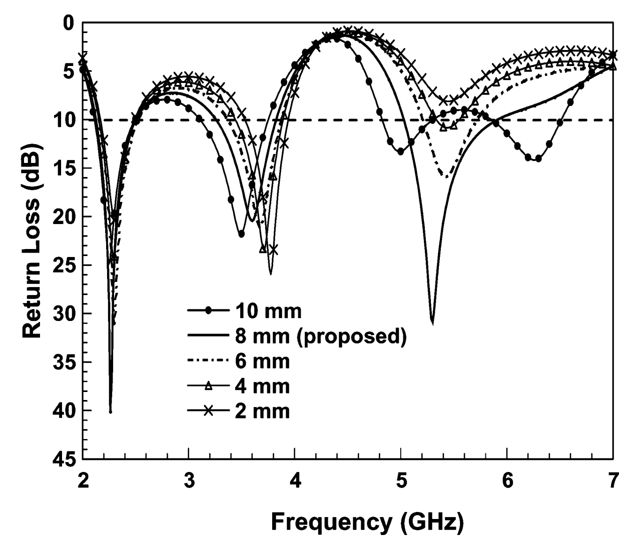

Fig. 6. Simulated return loss against frequency for the proposed triple-frequency monopole antenna with various L_2; other parameters are the same as listed in Table I.

in Fig. 2. Note that in these cases all the unmentioned dimensions are the same as listed in Table I. For the case without using the DGS (i.e., using the $20 \times 30\ \mathrm{mm}^2$ solid ground plane for the proposed antenna), a worse matching condition appears over the frequency band, while a resonant mode seems to form at about 3.6 GHz. It is the fundamental mode excited by the radiator of the rectangular patch loaded with the protrudent strips since the one-quarter wavelength when operating at 3.6 GHz (i.e., about 21 mm) is almost the same as the electric length along the side of the radiator. As for the case of the radiating patch without having the two protrudent inverted L-shaped strips (curve (iii)), the matching condition is still poor across the full band. However, two modes resonating at 2.3 and 5.04 GHz, respectively, become forming and without seeing the second resonant mode. This indicates that inclusion of the two inverted L-shaped strips in the proposed design will not only significantly improve the impedance matching conditions for the lowest and highest bands but also can excite an additional resonance at the second band. Finally, if we remove the horizontal strip from the cross-shaped feedline (curve (iv)), though the triple-resonance situation is almost not affected, the matching condition of the highest resonance becomes worse. For further examining the above excitation mechanism of the proposed antenna, the excited surface current distributions, obtained from the HFSS simulation, on both the radiator and the ground for the optimally designed antenna, as presented in Fig. 2, was studied. Fig. 3 shows the results for the three resonant frequencies at 2.26, 3.6, and 5.3 GHz. Obviously, for the lowest band excitation (2.26 GHz band), a large surface current density is observed along the central longitude portion of the DGS, whereas for the second-(3.6 GHz band) and the highest-band (5.3 GHz band) excitations, the current distribution becomes more concentrated along the protrudent strips and cross-shaped feedline, respectively. According to the observed phenomena in current distribution on the proposed antenna when operating at the three bands, we investigated the influence of the related geometrical dimensions on the impedance matching condition of the three resonant modes. First, the effect of the DGS to the matching condition at the highest operating band is studied. Fig. 4 presents the simulated results of the proposed antenna with slot width $W_{g2} = 7.5$, 8, and 8.5 mm for the defected ground. We found that the lowest resonant mode is shifted toward the higher frequency band when W_{g2} increases, whereas the two higher resonant modes are slightly affected. As for the second resonant mode, according to the current distribution shown in Fig. 3(b), it has been shown that large current density is concentrated on the radiator. Therefore, this was verified by adjusting the length L_5 of the inverted L-shaped strip to be the values of 2, 3, 5, and 7 mm, and Fig. 5 gives the simulated results. Note that $L_5 = 5\ \mathrm{mm}$ is the obtained optimal case. Obviously, for this design, varying the length of the patch's protrudent strip, as excepted, does not significantly change the triple-resonant mode but does shift the frequency of the second resonance mode. The second resonant mode moves

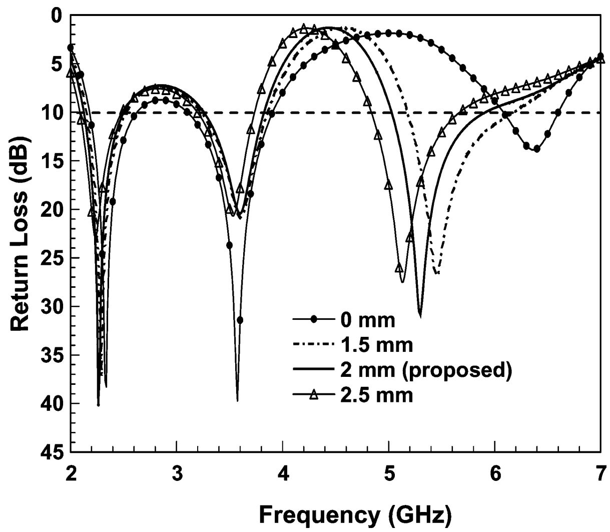

Fig. 7. Simulated return loss against frequency for the proposed triple-frequency monopole antenna with various W_{g1}; other parameters are the same as listed in Table I.

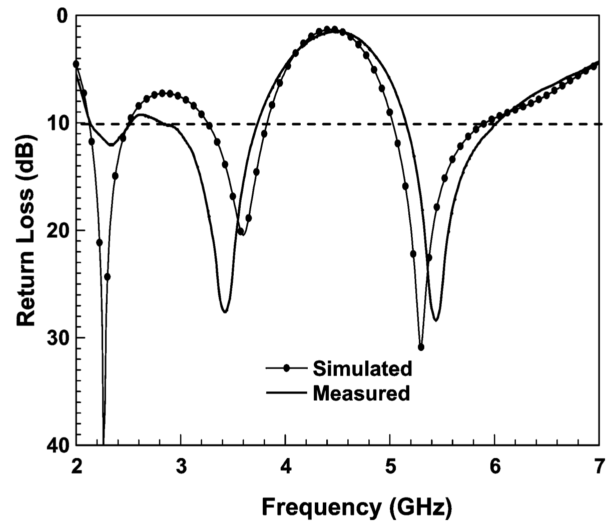

Fig. 8. Measured and simulated return loss against frequency for the proposed triple-frequency monopole antenna.

toward lower frequency band with L_5 increasing because the effective electric length along the radiator is lengthened when L_5 increases, whereas both the lowest and the highest dominant modes are only slightly affected. Considering the third (highest) resonant mode from the current distribution on the antenna, as shown in Fig. 3(c), a large current density was observed along both the cross-shaped feedline, especially on the horizontal strip, and the appropriate ground plane on the opposite side of the substrate. Thus, the tuning effect of strip length L_2 of the cross-shaped feedline on the impedance matching condition is examined and shown in Fig. 6. The varying dimensions of L_2 are 2, 4, 6, 8, and 10 mm. Here, the case of $L_2 = 2\ \mathrm{mm}$ represents that the proposed antenna is fed by a straight microstrip instead of a cross-shaped stripline. Obviously, varying the strip length L_2 would seriously affect the highest operation band impedance matching, whereas less change is seen for the first and second operation bands. Another parameter that may affect the highest resonance is the slot width W_{g1}. Fig. 7 presents the simulated results of return loss against the frequency of the proposed antenna with $W_{g1} = 0$, 1.5, 2 and 2.5 mm. Note that the case of $W_{g1} = 0$ means the slot of $L_{g1} \times W_{g1}$ does not exist. The third (highest) resonant mode is clearly found to move toward the lower frequency band if the ground is cut with this slot. With an increase in the width W_{g1}, the lowest resonant frequency of the third mode decreases, whereas those of the other two modes are almost unchanged. The above analyzed results are very much in accordance with that observed from the current distributions on the antenna and also very vital for designing such an antenna to obtain the desired triple-frequency bands.

III. Experimental Results

The prototype of the proposed antenna with optimal dimensions, as listed in Table I and depicted as curve (i) in Fig. 2, was constructed and experimentally investigated. The return loss against frequency for this triple-frequency antenna was measured by using the Agilent E5071C vector network analyzer and is presented in Fig. 8. For comparison, the simulated results are also plotted in this figure. Obviously, three resonant modes at frequencies of 2.31, 3.42, and 5.44 GHz were also obtained. The measured impedance bandwidths are about 380 MHz (2.14–2.52 GHz), 920 MHz (2.82–3.74 GHz), and 870 MHz (5.15–6.02 GHz), corresponding to an impedance bandwidth of 16%, 27%, and 16% with respect to the appropriate resonant frequencies over the three operating bands. For comparison, Table II lists the related simulated and measured data. Reasonable agreement between the simulation and the measurement is achieved beyond a frequency deviation of $\leq 5\%$ at the lowest resonant frequencies of the triple operating bands. However, when we took into account the effects of the SMA connector as well as the connecting cable, by which the antenna was fed, in HFSS simulation, such a frequency shift could not be improved. Contrarily, the frequency deviations at the two higher bands get larger. The difference may therefore be attributed to the mismatching between the connector and the antenna feeder.

TABLE II
Simulated and Measured Impedance Bandwidths of the Proposed Triple-Frequency Monopole Antenna

	f₁ (GHz)	*f₂* (GHz)	*f₃* (GHz)
	BW (%, GHz)	*BW* (%, GHz)	*BW* (%, GHz)
Simulated	2.26	3.6	5.3
	17, 2.13~2.51	16, 3.26~3.83	17, 5.03~5.91
Measured	2.31	3.42	5.44
	16, 2.14~2.52	27, 2.82~3.74	16, 5.15~6.02

The radiation characteristics such as radiation pattern, efficiency, directivity, and peak gain across the three operating bands for the proposed antenna have also been measured in a far-field range anechoic chamber with dimensions of $7\ \mathrm{m(L)} \times 3.25\ \mathrm{m(W)} \times 3.25\ \mathrm{m(H)}$ and a three-dimensional rotator. Fig. 9 presents the measured radiation patterns including the vertical (E_θ) and horizontal (E_ϕ) polarizations in the azimuthal direction (x-y plane) and the elevation direction (x-z and y-z planes) when operating at 2.45, 3.5, 5.25 and 5.75 GHz

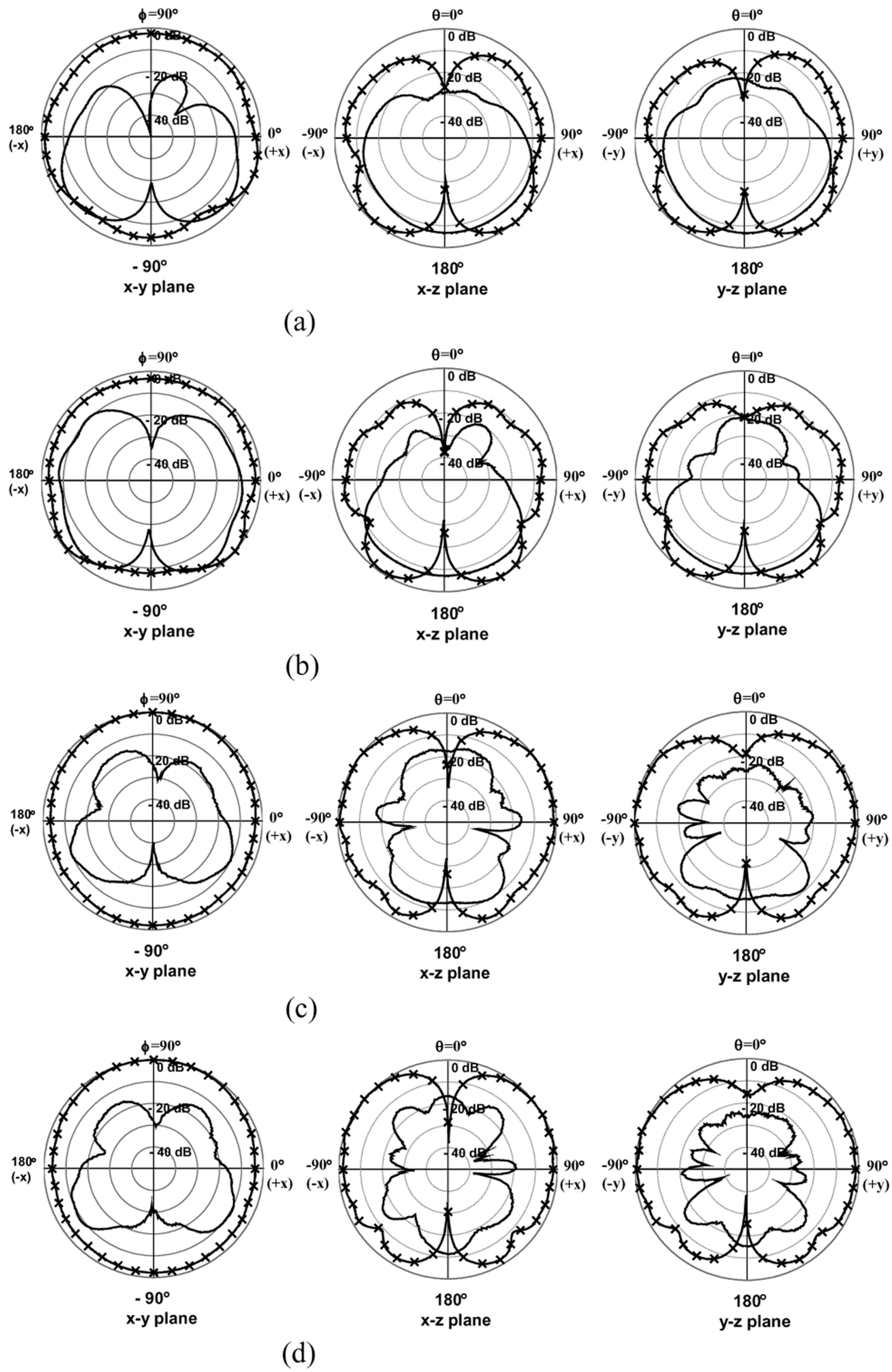

Fig. 9. Measured radiation patterns for the proposed triple-frequency monopole antenna. (E_θ : —x x x—, E_ϕ : ——) at (a) 2.45 GHz, (b) 3.5 GHz, (c) 5.25 GHz, and (d) 5.75 GHz.

for WLAN and WiMAX applications. Because of the symmetry in structure, rather symmetrical radiation patterns are seen in the x-z and y-z planes as depicted in the plots. In addition, very monopole-like radiation patterns with nearly omnidirectional radiation in the azimuthal plane and nearly conical patterns in the elevation planes are observed. In addition, it is also found that the E_θ and E_ϕ components of the patterns in both x-z and y-z planes for operating at 2.45 and 3.5 GHz are seemed to be more comparable than those operating at 5.25 and 5.75 GHz. This electromagnetic phenomenon can be ascribed to the more horizontal components of the surface current on the antenna when operating at 2.45 and 3.5 GHz than at 5.25 and 5.75 GHz, as shown in Fig. 3. Also note that measurements at other operating frequencies across the bandwidth of each band

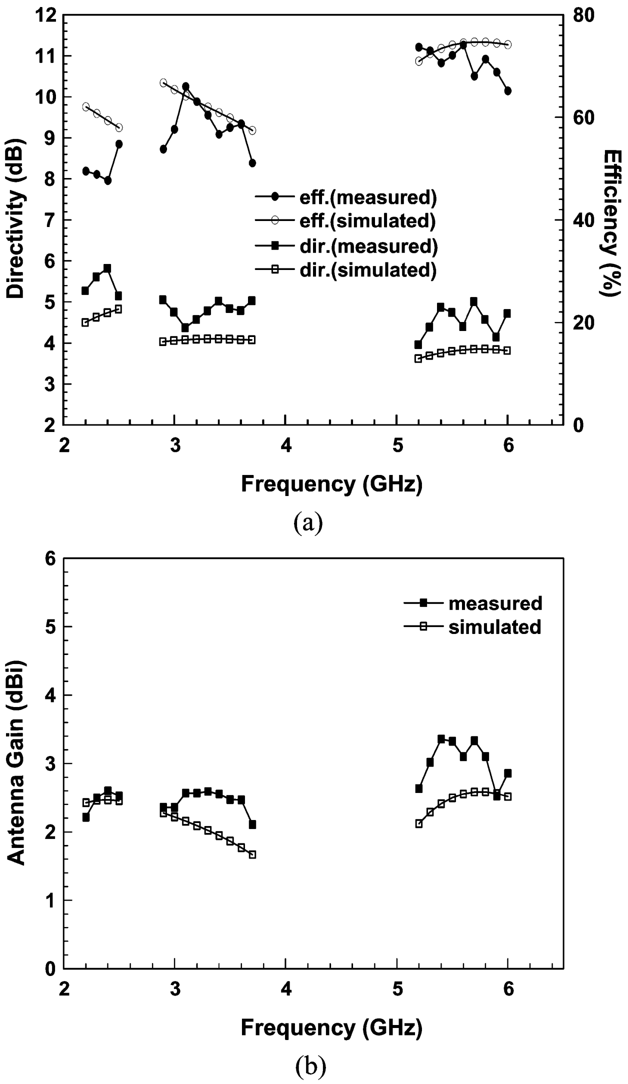

Fig. 10. Measured and simulated (a) directivity and radiation efficiency, and (b) peak gain across operating bands for the proposed triple-frequency monopole antenna.

show radiation patterns similar to those plotted here. Finally, Fig. 10 shows the measured and simulated radiation efficiency, directivity and peak gain of the proposed design for frequencies across the triple operating bands. The average efficiencies for the three bands are about 50, 58, and 71%, respectively, in measurement, whereas 60, 62, and 74%, respectively, in simulation. For directivity, the measured average values are 5.5, 4.8, and 4.5 dB, whereas the simulated results are 4.7, 4.1, and 3.8 dB, respectively, over the three frequency bands. It indicates that as the operating band gets higher, the efficiency increases while the directivity decreases. The reason could be that when operating at the lower frequency, the current on the antenna is more in-phase and concentrated in the same direction to thus make a higher directivity. The peak antenna gains were measured by applying the gain comparison method, in which a precalibrated standard gain antenna is used to determine the absolute gain of the antenna under test, and shown in Fig. 10(b). The ranges of measured gains are about 2.2–2.6, 2.1–2.6, and 2.5–3.4 dBi with an average value of 2.46, 2.45, and 3.0 dBi, respectively, across the triple bands. Agreement between the measurement and simulation seems well beyond a difference of ≤ 0.5 dB over the highest frequency band.

IV. Conclusion

A novel microstrip-fed antenna design based on the patch monopole for a triple-frequency operation has been presented with simulated and measured results. With the skills of defecting the ground plane, protruding the patch with dual protrudent strips, and feeding the patch with a cross-shaped stripline, the proposed antenna can excite triple-resonances and has a suitable radiation performance to cater to the operation requirements of both the 2.4/5.2/5.8 GHz WLAN and the 3.5/5.5 GHz WiMAX communication systems. The antenna prototype has been constructed and measured, and shown to match well with the numerical prediction. Also, the effects of existences of the DGS, the prudent strips, and the cross-shaped stripline, and varying the dimensions of these structures on the antenna resonant frequencies and impedance bandwidths have been presented.

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